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Inertial and diffusive pore pressure fields in porous media

Summary

Mircoseismicity based reservoir characterization often assumes that microseismic events are triggered by a changing pore pressure field around the injection well. This effect can be modeled by a diffusion equation for pore pressure, if coupling between solid stress and fluid pressure is neglected. However, a full description of stress evolution, including pressure-stress coupling and inertial effects like wave propagation, is provided by Biot's equations of poroelasticity. Here we use a finite-difference scheme for solving Biot's equations in the time domain and show the behavior of the Biot slow *P*-wave for different regimes.

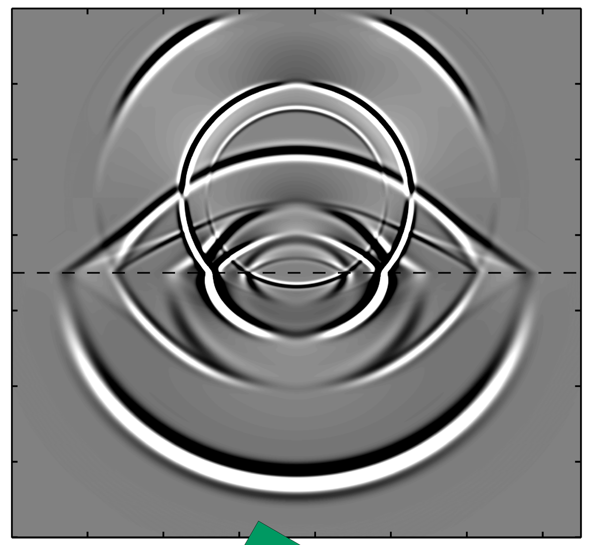
Biot equations

Fluid saturated porous media
Biot equations of poroelasticity

$$(1)\quad \begin{aligned} \rho^b \ddot{u}_i + \rho^f \ddot{w}_i &= \tau_{ij,j} \\ \rho^f \ddot{u}_i + \rho^m \ddot{w}_i &= -p_{,i} - b\dot{w}_i \end{aligned}$$

$$(2)\quad \begin{aligned} \tau_{ij} &= 2\mu\,\varepsilon_{ij} + (\lambda_c \varepsilon - \alpha\, M\zeta)\,\delta_{ij} \\ p &= -\alpha\, M\varepsilon + M\zeta, \end{aligned}$$

Characteristic relaxation frequency ω_c
Numerical FD modeling
(Krzikalla and Müller, 2007)



$\omega \gg \omega_c$

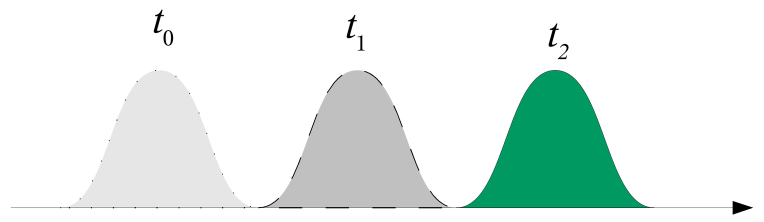
$\omega \ll \omega_c$

High-frequency regime

Short-term response with $t \ll \omega_c^{-1}$
inertial terms prevail
three wave modes propagate *P*, *S*, slow *P*
with slow *P*-wave velocity
(Pride and Haartsen, 1996)

$$(3)\quad v_{P_s} = \sqrt{\frac{P_{dry} M}{\rho^m H - 2\rho^f \alpha M + \rho^b M}}$$

poroelastic moduli P_{dry}, H, M,
densities ρ^m, ρ^b, ρ^f

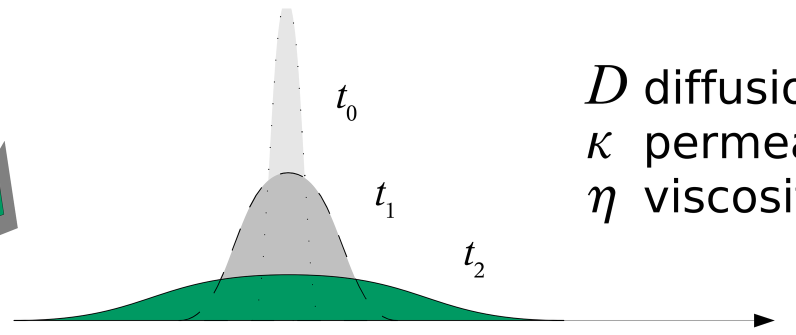


interaction at intermediate frequencies
wave induced diffusion
mesoscopic effects

Low-frequency regime

Long-term response with $t \gg \omega_c^{-1}$
friction dominates
stress equilibrium + diffusion equation

$$(4)\quad \dot{p} = D\,\nabla^2 p \quad \text{with} \quad D = \frac{\kappa\, M\, P_{dry}}{\eta H}.$$



D diffusion coefficient
κ permeability
η viscosity

Slow P-wave behavior

Fluid injection source
⇒ excitation of pore pressure
Diffusion solution is (Rudnicki, 1986)

$$(5)\quad p = \operatorname{erfc}\left(x \,/\, \sqrt{4Dt}\ \right).$$

From a numerical point of view, the diffusive character of the slow *P*-wave implies a strong stiffness of the system when it is excited at frequencies much lower than ω_c.

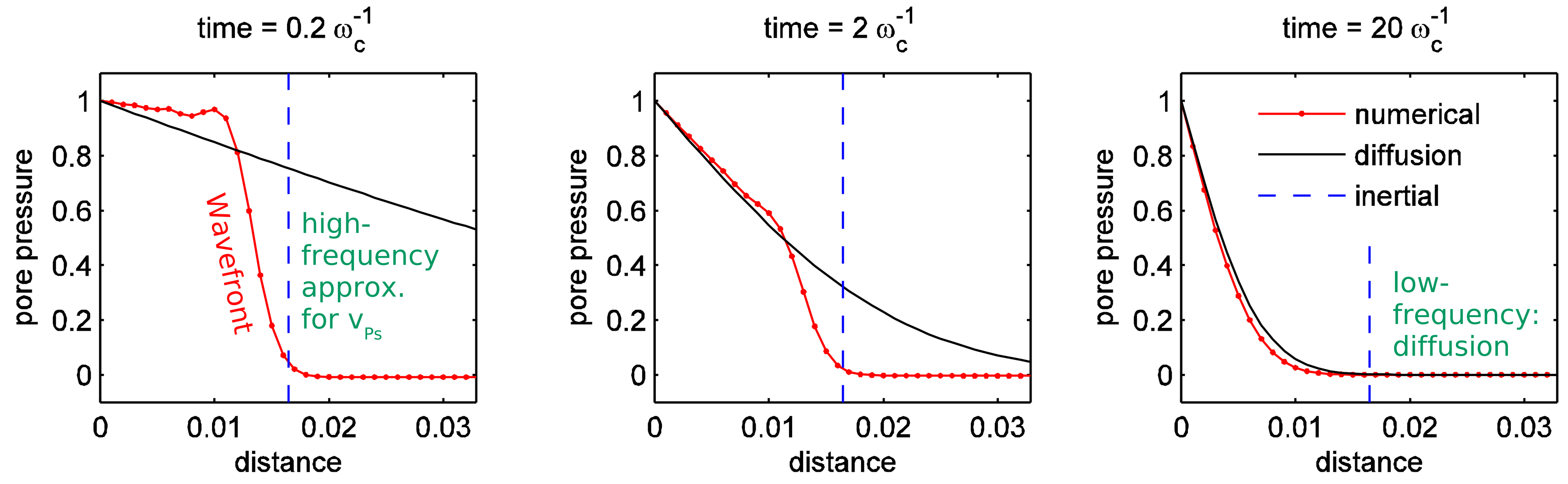


Figure 1: Pore pressure evolution as a function of distance *x* for a step loading at *x=0*. The short-term response is of propagation type ($x = v_p t$) while the long-term response is diffusive: $p \sim \operatorname{erfc}(x)$, see eq. (5).

Poroelastic rheology

If the frequency is high, pore pressure does not have time to relax and the rock behaves stiff. For low frequencies, the rock sample can drain and therefore behaves as soft as dry rock.

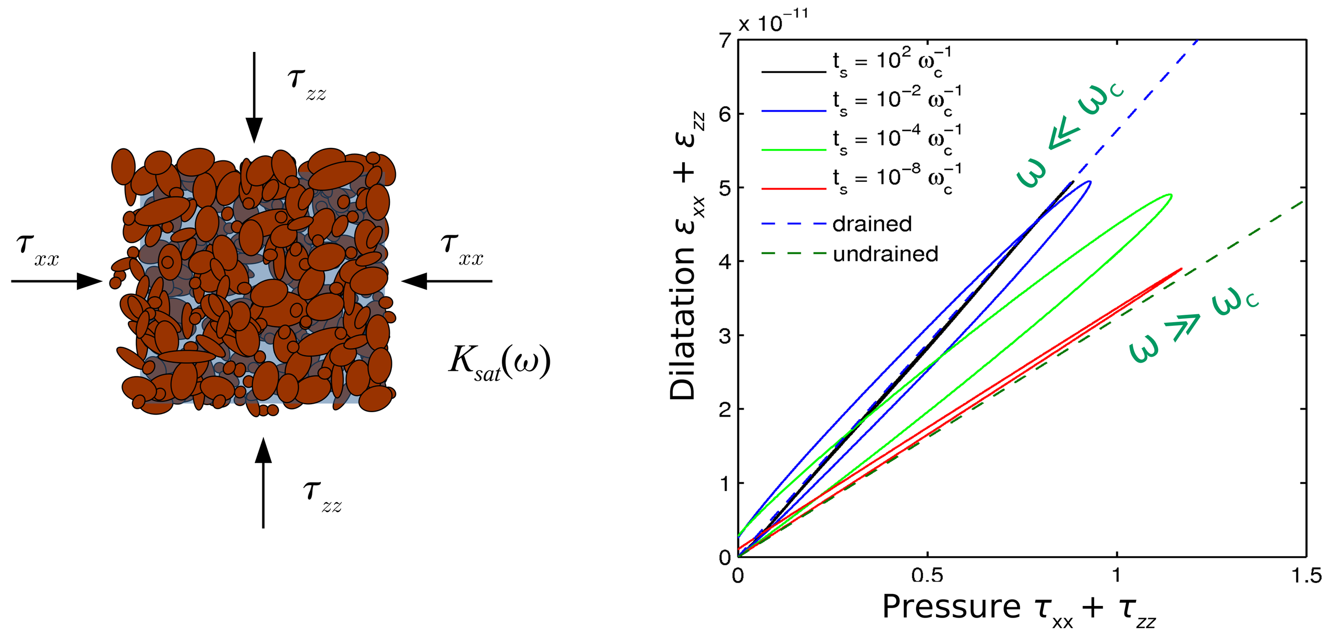


Figure 2: Hysteresis curves for transient isotropic loading of a 2D saturated rock sample. Depending on loading frequency, drained or undrained bulk moduli are observed.

Three FD examples

Frequency-dependent reflection

Poroelastic effects change the behavior of the reflection coefficient. Depending on the frequency regime, the incident wave is either converted into a diffusive slow *P*-wave or two propagating waves.

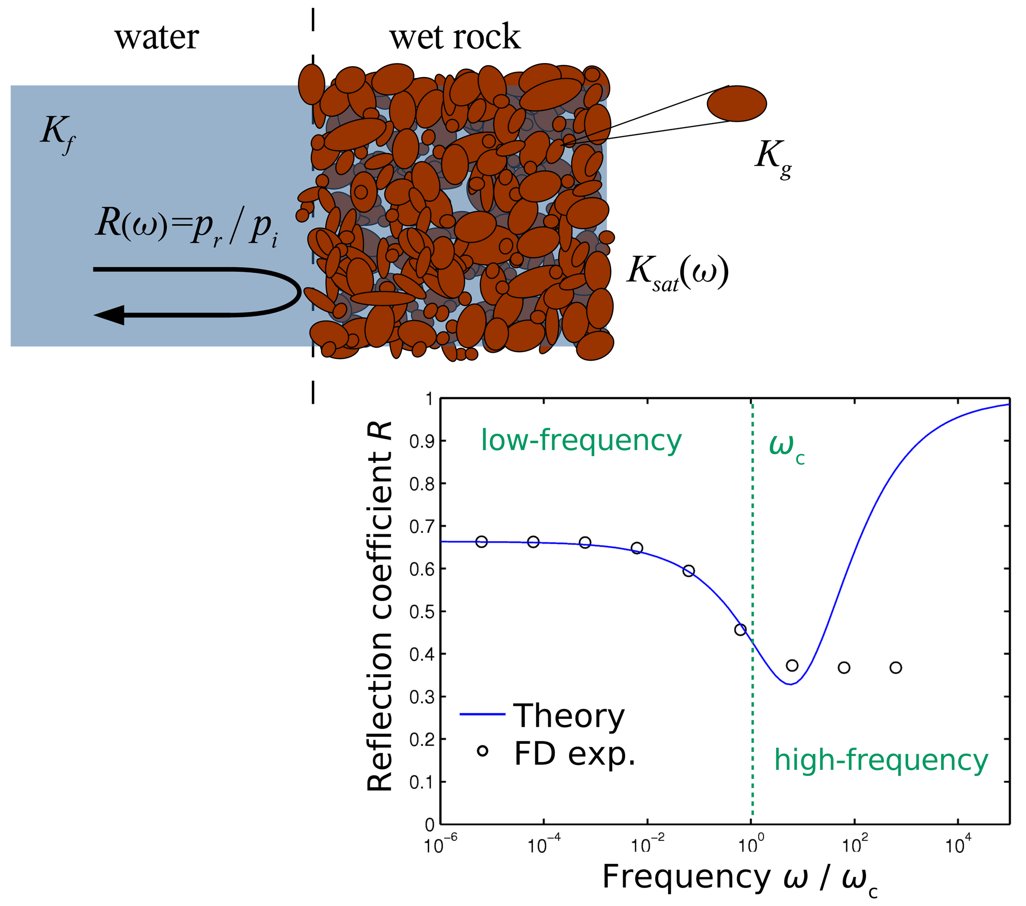


Figure 3: Reflection coefficient for a water-rock-interface. Theoretical solution is taken from Gurevich et al. (2004). Note that for high frequencies, the theory is not valid any more.

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